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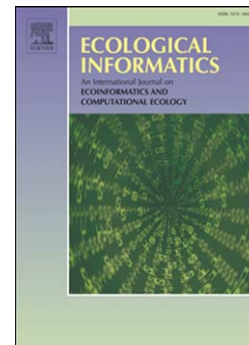
Modelling spatial distributions of alpine vegetation: A graph theory approach to delineate ecologically-consistent species assemblages

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Abstract:

Safeguarding biodiversity has been one of the most important issues on the environmental and forest policies agenda since the 1990's. The problem remains in terms of decisions and knowledge on where to set appropriate conservation targets. Hence, we need detailed and reliable information about habitat structure and composition and methods for estimating this information over the whole spatial domain. In answer to this target, in France, the Ministry of Ecology launched an ambitious project to map the terrestrial vegetation at a scale of 1:25 000 known as CarHab. This project initiated in 2011, will be used as a strategic spatial planning tool in answer to key issues in relation to biodiversity, conservation, green infrastructures and to report on the conservation status of habitats and species of community interest. We use species-distribution models (SDMs) to identify areas that are ecologically suitable for the presence of species based on specific habitat characteristics. Available techniques using graph theory enable identification of groups of species (assemblages) based on ecological affinities. Species co-occurrences (present within the same assessment plot), revealing a shared ecological niche, are analysed using algorithms derived from graph theory in order to define different nodes of species affinities. Thus, the resulting assemblages are based on ecological similarities. Hence, these assemblages are used to develop models of the potential distribution of alpine vegetation communities. The BIOMOD platform is used to facilitate the simultaneous implementation of different modelling approaches that can be compared in order to choose the most suitable and accurate for each species assemblage obtained from graph theory. Using the different relevant spatially explicit results provides a more comprehensive vision of the communities' spatial distributions.

Modelling spatial distributions of alpine vegetation: A graph theory approach to delineate ecologically-consistent species assemblages

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I. Introduction

Predictive models of species distributions are being increasingly used to address questions related to the ecology, biogeography, and conservation of species (see Peterson, 2007). Detailed knowledge of ecological and geographic distributions of species and vegetation is fundamental for conservation planning and forecasting (Ferrier 2002, Funk and Richardson 2002, Rushton et al. 2004) and for understanding ecological factors of spatial patterns of biodiversity (Rosenzweig 1995, Brown and Lomolino 1998, Ricklefs 2004, Graham and Hijmans 2006).

In the framework of the French national project CarHAB, this research aims at exploring the potential of predictive vegetation modelling to improve and support detailed vegetation mapping. CarHAB project aims at mapping natural and semi-natural vegetation of the French territory at a scale of 1:25 000 (EEA 2014). It addresses three major challenges based on stakeholders needs: i) to provide a comprehensive inventory of vegetation and habitats, ii) to assess their conservation status and iii) to provide the baselines for related planning and conservation projects. Vegetation mapping relies on achieving base-map learning about the physiognomic and environmental characteristics of vegetation. These base-maps are aimed at providing support for the extrapolation of phytosociological surveys conducted in the field before the completion of the final vegetation maps based on remote sensing data derived from different satellites. The work presented was tested in a complex mountainous environment in the French Alps (Isere Department). In all, the approach developed opens innovative ways towards a replicable classification scheme for vegetation mapping over open environments based on graph theory to delineate ecologically-consistent species assemblages to be modelled.

II. Background and Study Area

The study area is a testing ground on a crystalline mountain range (Belledonne, Grandes-Rousses, Ecrins, Oisans; Figure 1), extending to 5000 km² and located in the Isère French Department. The area is dominated by siliceous grasslands from sub-alpine and alpine belts ranging from 1,500 to more than 3,000 meters above sea level – the timberline being at about 2,200 m. Sub- and alpine grasslands show a great diversity according to ecological factors, such as temperature, elevation and solar radiation. Topographic position at the alpine belt is a key factor because it influences snow cover duration, which is known to determine plants' ecophysiology and adaptation. Micro-topography and consequent rapid changes of environmental conditions in space and time are also important features of alpine glacier-shaped landscapes that strongly influence the plant community properties.

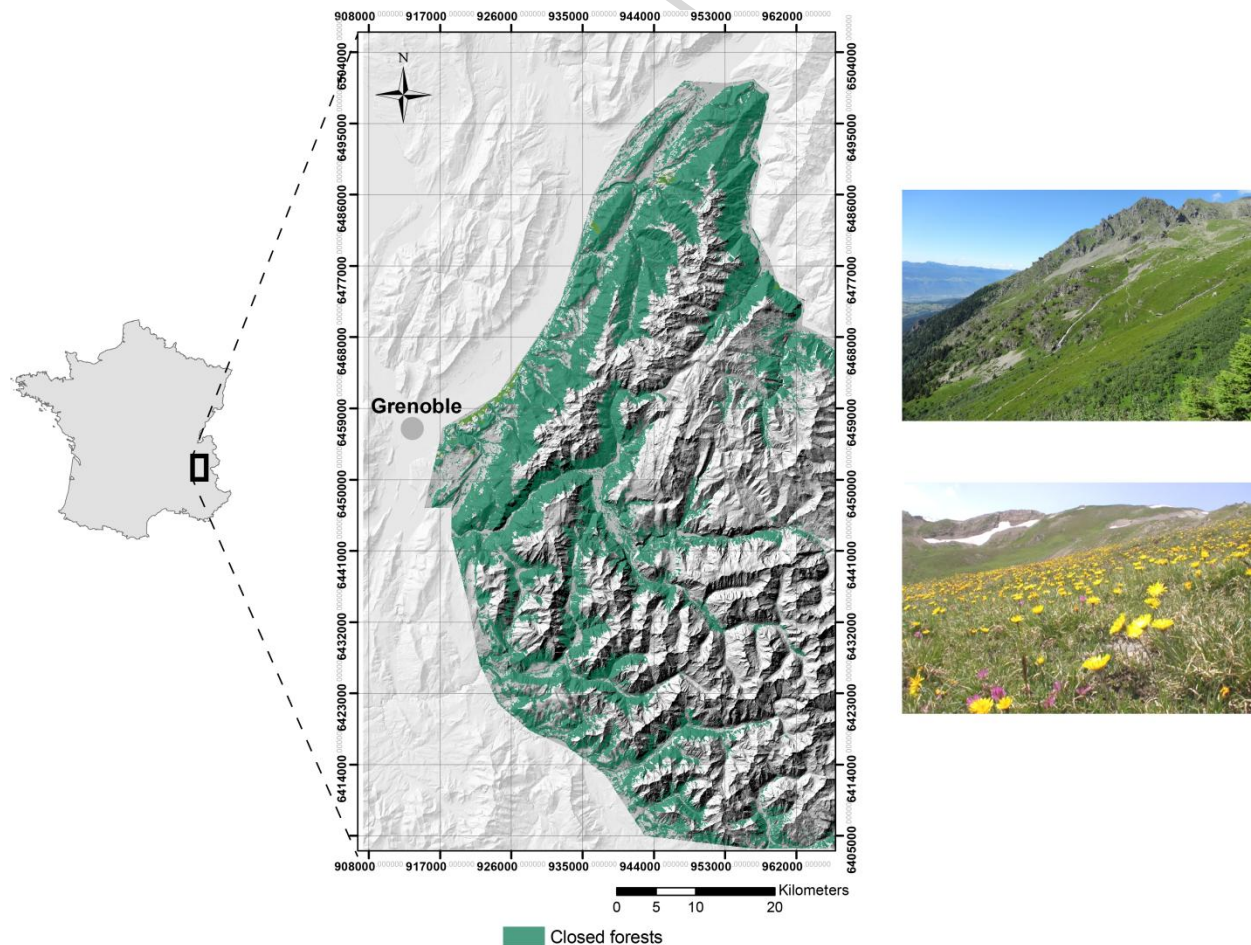


Figure 1: Belledonne, Grandes-Rousses, Ecrins, Oisans - mountain range located in the Isère French Department.

III. Methods

III.1. Graph theory to uncover species assemblage patterns

Graph theory has recently gained much attention in various fields of science. In the ecological sciences, it was first used to analyse webs of real biological interactions, such as food-webs, gene and protein networks and pollination networks (Proulx et al. 2005). The first application of graph theory to vegetation-plot data (species*sites table) was conducted by Yarranton (1973) to test the homogeneity of phytosociological tables. Dale (1977a, b) suggested later that graph theory could be used to detect plant species interactions in temperate forests at different scales. The method enables the properties and behaviour of networks to be quantified and visualized with friendly graphical outputs.

A graph is a mathematical object corresponding to a network. It is composed of a set of units, called nodes, connected by edges. A module is a subset of highly-connected nodes with looser connections to the rest of the graph (Figure 2-b). The nodes can represent units at most levels of the biological hierarchy (e.g. from genes to proteins, from individuals in a population to species in a community). Edges usually represent interactions between nodes. The co-occurrence of species that is derived from vegetation-plot data represents a sort of statistical interaction. Depending on the scale of the dataset (plot size and extent), the co-occurrence species can be linked to different kinds of ecological processes that graph theory can help to explain. Dale (1977a, b) showed facilitation patterns in forests with very fine-scale data. Fine-scale data like in this study are relevant to look at the ecological requirements of species (niche). Yet large-scale data could be used to reveal *nestedness* and other biogeography-related patterns of communities' species composition.

Here the goal is to delineate alpine-grasslands plants' assemblages based on the ecological requirements of species in order to use ecological gradients to model assemblages' distribution patterns. We start with the hypothesis that all species have specific habitat requirements, which can be described by habitat factors. These factors are inter-related to critical habitat characteristics, e.g. to those of vegetation and soil, but also areas surrounding the habitat (e.g. the spatial structure of landscape elements). The assemblages were then defined by applying a graph theory approach to a dataset of 4,280 phytosociological vegetation plots corresponding to acidophilous sub- and alpine grasslands, collected by the National Botanical Conservatory of the Alps (CBNA). Information within plots includes location and plant species list (abundance) occurring within vegetation' stands. Our concern was to elaborate species assemblages (or modules) that are not constrained by phyto-sociological principles but based on the species co-occurrence at the monitoring plot level.

The co-occurrences between pairs of species were derived from the vegetation-plot dataset. They were then translated into a graph where the nodes represent each species and the thickness of edges represents the degree of co-occurrence between pairs of species (

Figure 2). We used the U index (Bruehlheide 2000) as a statistical measure of co-occurrence (edge weight) instead of the exact co-occurrence within the dataset. Edges with a low level of co-occurrence (i.e. a low level of information) according to a certain U threshold were removed to provide a sharper graph without losing valuable information (Tumminello et al. 2011a,b).

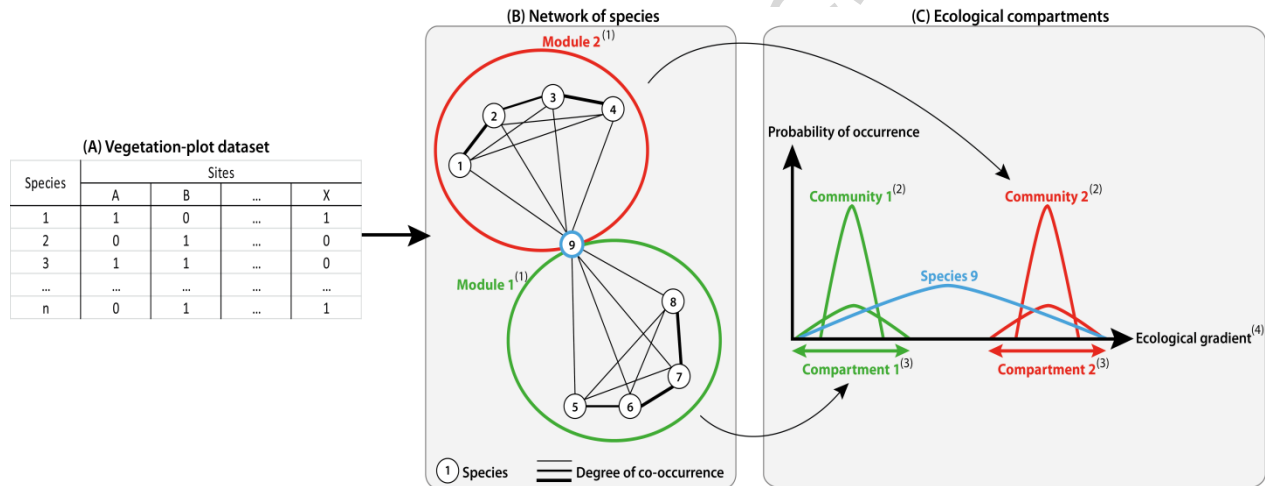


Figure 2: Construction of a network of species from vegetation-plot data and ecological interpretation: (A) vegetation-plot dataset consists of sites/species tables with presence/absence data; (B) an index of co-occurrence between pairs of species (U) is computed from the table and allows a network to be constructed: the nodes represent each species and the edge thicknesses the index U ; (C) here the structure of the network is assumed to be caused by ecological requirements of species: each cluster of nodes (representing species with similar ecological requirements), called module (1), is a representation of plant communities (2) based on their ecological affinities. These communities can then be associated with specific ecological compartments (3) along ecological gradients (4).

Co-occurrence of pairs of species within a particular plot is assumed to be caused mainly by the same or similar ecological requirements (

Figure 2 (C); i.e. habitat filtering, Lortie et al. 2004) with no detection of biotic interactions between species (biotic filtering). In this way using graph theory enables identification of groups of species based on ecological affinities.

A first level of analysis of the species' assemblage patterns from a graph structure is to detect the presence of modules of highly-interconnected species. Among a large array of module detection algorithms developed by the graph theory community we used an algorithm derived from the information theory called 'maps of random walks' also referred to as infomap (Rosvall and Bergstrom 2008). It allows the delineation of modules where species are much more likely to occur together in real-

world communities rather than species from other modules because they share similar ecological requirements.

A second level of analysis of a graph structure is to analyse in more detail the role of each node (species) according to their pattern of intra- and inter-module connections (Guimerà and Amaral 2005). They define a *within module degree* (z) which measures how well-connected is a vertex to other vertices inside the module and a *participation coefficient* (C) which measures how well-distributed the edges of a vertex are among other modules. A species with both high z and low C - called 'provincial hubs' - is believed to be a good indicator of module habitats conditions (i.e. called here ecological compartment) because it shares ecological requirements with many other species of the same module. We expected these species to be widely distributed among plant communities inside this particular ecological compartment, whereas species with low z and C - called 'peripheral hubs' - have stronger ecological requirements and are very likely to occur in more specialized plant communities in more constrained ecological sub-compartments. This ratio z/C is particularly interesting when studying species strategies (ubiquist/endemic/indicator) and will help us choose the most 'provincial' species to represent best the ecological behaviour of each module.

III.2. Ecological gradients

A small set of continuous ecological variables (Table 1) was recognized to affect spatial distribution of grasslands alpine species at the mapping scale used (25 m grid resolution on 5,000 Km² of study area). Plot size (4-50 m²) is smaller than variable resolution (25*25 m) but we assumed here the spatial homogeneity of species assemblages at the pixel level. Therefore, species-environment relationships and variability were well-captured at this resolution.

Table 1: Ecological gradients used to characterize species-environment relationships for the species distribution models (SDMs). All variables have a 25m resolution (grid, raster)

Gradients	Relevance	Description	Source and references
Altitude	Indirect variable for temperature considered as a major ecological factor affecting plant and vegetation distribution particularly in mountain environments	DEM from contour lines	IGN, France
Total Insolation	Direct variable through direct impacts on plants physiology and indirect variable on snow cover duration	Total solar energy, on each pixel (direct + diffuse insolation)	DEM derived, Wilson & Gallant (2000)
Topographic Wetness index	Indirect resource variable accounting for soil water content	Modified Topographic Wetness Index : $\log(SWI)$	DEM derived, Boehner et al. (2002)

Degree of convexity	Indirect variable affecting snow cover duration, local temperature and wind conditions	Topographic analysis : radius of 50m for micro-topography, DEM derived, radius of 500m for main relief features	Weiss (2001)
Spatial dependence	Climatic gradient across study area (NW/SE gradient)	log(latitude/longitude)	Derived from localisation

III.3. Modelling platform

We used a multi-modelling platform, Biomod2 (see Thuiller et al. 2009; Thuiller et al, 2013), which allowed the use of 10 statistical models to calibrate the relationship between explanatory variables and occurrences of modules (Table 2).

Table 2: Statistical models of Biomod2 platform

Type	Model	Key references
Regressions	GLM Generalised Linear Models	Guisan <i>et al.</i> , 2002; Pearce & Ferrier, 2000 ; Vincent and Haworth, 1982 ; Guisan <i>et al.</i> , 1998
	GAM Generalised Additive Models	Yee & Mitchell, 1991; Guisan <i>et al.</i> , 2002; Pearce & Ferrier, 2000
	MARS Multivariate Adaptive Regression Splines	Friedman, 1991
	FDA Flexible Discriminant Analysis	Hastie, T., Tibshirani, R. and Buja, A.,1994; Manel, D., Dias, J. M., Buckton, S. T. and Ormerod, S. J.,1999
Decision trees	CTA Classification Tree Analysis	Breiman <i>et al.</i> , 1984
	RF Random Forest	Breiman, 2001
Regression on decision trees	GBM Generalized Boosting Model	Ridgeway 1999
Environmental envelope	SRE Rectilinear Envelope	Busby, 1991; Walker & Cocks, 1991
Learning methods	Maxent Maximum entropy	Phillips <i>et al.</i> , 2005 ; Phillips <i>et al.</i> , 2006
	ANN Artificial Neural Networks	Pearson <i>et al.</i> , 2002

The resulting models were compared based on their relative performance in fitting the observed data (Elith et al. 2006). A first statistical assessment was performed using ROC sensitivity analysis, which was calculated for each model on 1,000 repetitions using 75 per cent of the sampled data. Statistical assessment was also supported with expert assessments conducted on the final distribution maps. Both outcomes were combined to produce the best distribution models that were used at the end for mapping ecological compartments.

IV. Results

IV.1. Species network

Figure 3 shows the resulting network derived from vegetation-plot data after application of the co-occurrence index (U) threshold and filtering on siliceous alpine grasslands species. The U index value – empirically set to 15 – results from a trade-off between (i) an excessive amount of low-level information (i.e. low U, poorly-connected species) but high number of species and (ii) high-level information (i.e. high U, highly-connected species) but low number of species. Modules 1 and 3 are very sharp owing to species with very low participation coefficient on average. Modules 2, 4 and 5 are fairly sharp with relatively higher participation coefficients. Module 6 is significantly connected to its neighbours through ‘connector-hub’ species and, therefore, was not modelled. For each module, species showing the best C/z profile (low C and high z) were selected as indicator species.

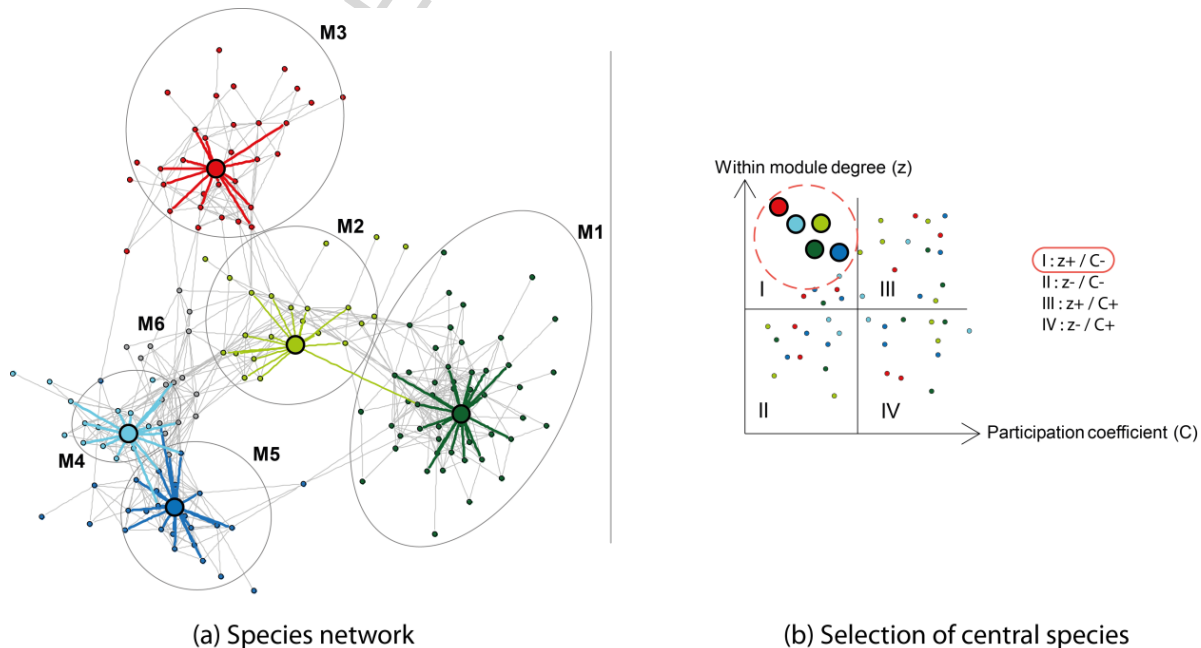


Figure 3: Network of 166 species of siliceous alpine grasslands with 697 edges. (a) Modules are labelled according to Table 1; one central species is highlighted for each module together with edges to its neighbours. (b) C/z

parameter space helps characterize each species and module role in the network; central species are chosen within the upper left square of provincial hubs (I). Following and simplifying Guimerà and Amaral (2005) other principal roles of nodes are peripheral nodes (II), connector hubs (III i.e. module 6) and non-hub connector (IV).

Species inside a module are linked with each other by their ecological affinities (common niche) and not by botanical characteristics, supporting the use of ecological datasets to predict vegetation potential distribution.

IV.2. Modules, ecological compartments and indicator species

Based on a modularity analysis and on an expert examination of the resulting species' network, 5 assemblages (M1, M2, M3, M4, M5) were selected (Table 3) for their wide representation in the field, their botanical consistency and their ecological dissimilarities. The modules are exclusive and therefore, in the modelling process, the presence points of a specified module were considered as absence points for all other modules.

Table 3: Expert characterization of modules yielded by the infomap modularity analysis and indicator species. (*) Module 6 was not modelled, providing its transitional positioning (high C value of species); the resulting ecological compartment strongly overlaps with the ones of other modules.

Modules	Number of plots	Expert characterization	Indicator species
1	125	Subalpine, cool and humid, tall-herbs communities	<i>Agrostis agrostiflora</i> , <i>Imperatoria ostruthium</i>
2	124	Subalpine, mesophilous, <i>Nardus stricta</i> grasslands	<i>Arnica montana</i> , <i>Potentilla aurea</i> , <i>Pseudorchis albida</i>
3	425	Subalpine, thermophilous, open <i>Festuca paniculata</i> grasslands	<i>Potentilla grandiflora</i> , <i>Senecio doricum</i> , <i>Centaurea uniflora</i>
4	250	Alpine, long snow cover duration (chionophilous species), vegetated snow-patches	<i>Veronica alpina</i> , <i>Omalotheca supina</i>
5	312	Alpine, short snow cover duration (cryophilous species), alpine open grasslands, swards	<i>Festuca halleri</i> , <i>Minuartia sedoides</i>
6	(*)	Alpine, medium snow cover duration, alpine grasslands	<i>Phyteuma hemisphaericum</i> , <i>Carex sempervirens</i>

IV.3. Modelling results

Using the 6 ecological gradients and modules' presence point data, we computed 10 species-distribution models (SDMs) for each of the 5 alpine species assemblages delineated by the graph approach in order to predict the potential distribution of their ecological compartments.

Four types of models showed ROC cut-off values above 0.85 – the threshold above which a model is considered here to have a good sensitivity or sufficient statistical relevance. The models that performed best were a GLM and a GAM, an RF, a GBM and a MaxEnt (see Table 2). The GLM successfully handled the expert assessment stage because it provided maps with both consistent probability levels and spatial extent closest to reality. MaxEnt also showed good spatial extent but low-probability levels whereas other types of models showed a trend to either over-estimate or limit spatial extent. For all models, around 80 per cent of presence data were properly predicted on average (sensitivity relevant) with relatively weak differences among modules. The same percentage and pattern were properly predicted for absences data. The importance of variables was in agreement with expert knowledge and underlined altitude as the key ecological factor influencing species-environment relationships. Close examination of the importance of variables is, nevertheless, beyond the scope of this proceedings paper. It is worth noticing that the degree of convexity at small scale (radius of 50m) did not show any statistical significance.

IV.4. Resulting map

At the end, all best-performing models (only GLMs) were mapped together (Figure 4). Each grid-cell was assigned to the model with the highest probability only if the differences with all other modules' probabilities were higher than 0.2. Otherwise, if the difference with another module was lower than 0.2 it was labelled as an overlap grid-cell (not shown here). Thus, the map represents the cores of the ecological compartments. Probabilities lower than 0.5, indicating a weak probability of occurrence; have clearer colours on the map in order to identify the zones of modelling uncertainty.

At the end, the different ecological compartments when mapped together present coherent spatial extents and probabilities with very good landscape coverage across the study area.

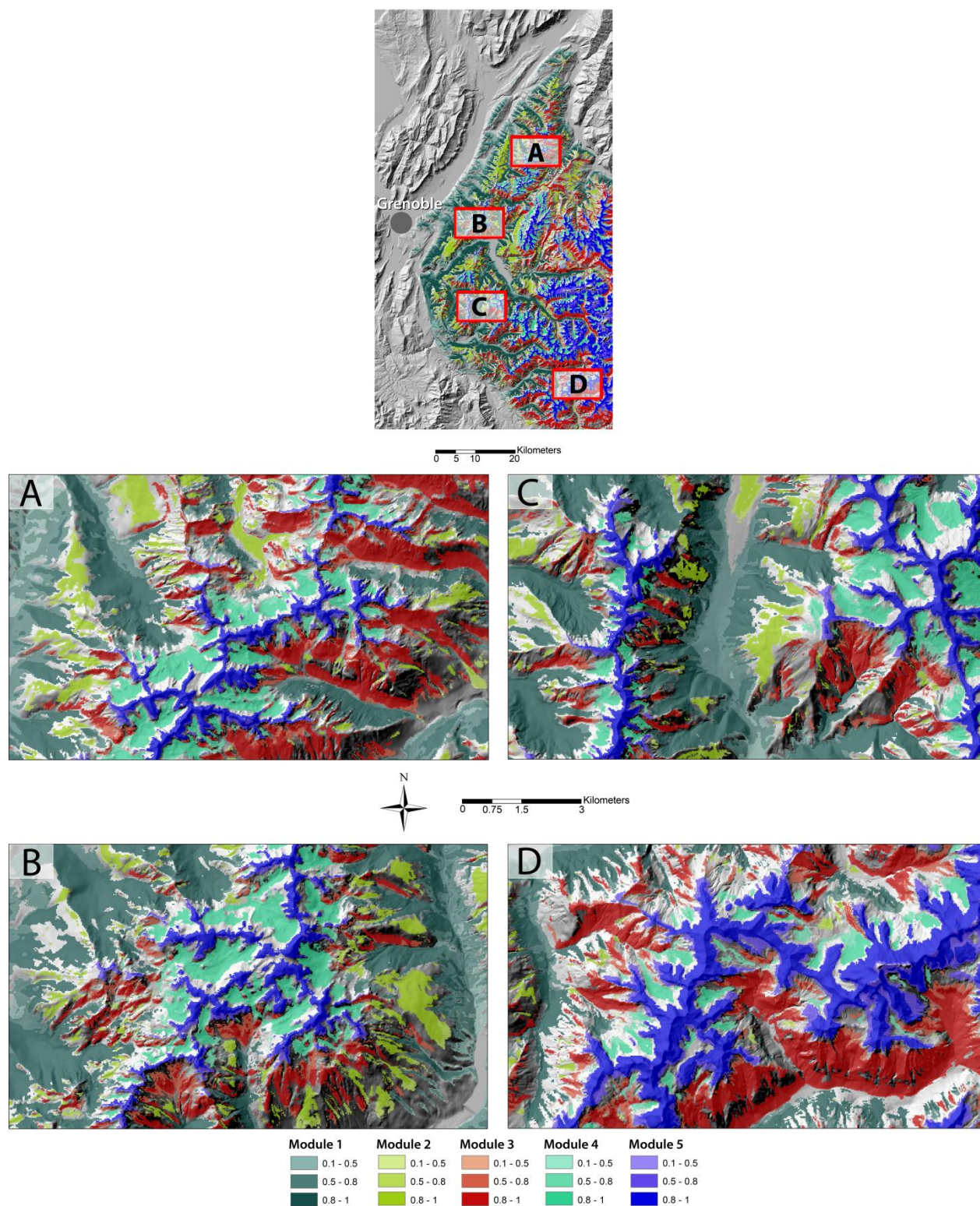


Figure 4: Example of modelling results for all compartments mapped together: (A) North Belledonne; (B) Lac Blanc area; (C) Lac du Vallon area (D) part of Ecrins' National Parc. Only non-overlapping results are shown to focus on the 'core areas' of ecological compartments. Models are numbered according to Table 3.

V. Discussion

Application of graph theory to vegetation-plot data combined with species distribution models has revealed ecologically-coherent species' assemblages and consistent ecological compartments' distribution. Compared to classical ecological clustering using environmental data, this modelling method yields ecological compartments that take into account vegetation's ecological requirements. This approach was successful to reveal gradual changes in environmental conditions: probabilities gently follow the topographic gradients, which are typically marked in the mountain environment. The transitional zones (i.e. the overlaps between ecological compartments) which represent 22.5 % of the area were in most cases ecologically relevant. The most frequently found were the transition between nival and cryophilous conditions (between modules 4 and 5: alpine belt) and the transition between mesophilous and thermophilic conditions (modules 2 and 3: subalpine belt).

Applying SDM at the landscape scale using explanatory variables derived from Digital Elevation Model (DEM) with a resolution of 25 m is quite rare in the literature. However, these variables, chosen to be close to plants' direct resources (e.g. total insolation for solar energy or topographic wetness index for soil water content) and generics for plants' pattern delineation in mountains' environments, are relevant to predict ecological compartments. Besides, it makes it useful to vegetation scientists because at this scale predictive maps are close to their on-ground perception.

Significant explanatory variables of species' assemblages' distributions are in accordance with our models. Altitude and total solar radiation were the most important variables, followed by the large-scale topographic position (convexity with radius of 500m). The spatial dependence variable played also a significant role, especially in the delineation of thermophilic subalpine ecological compartment (module 3) as it occurs much more in the southern part of the area. The small-scale topographic position (convexity with radius of 50m) seemed not to account for micro-topographic patterns due in part to the mismatch of resolution with the DEM used (25 m). Thus, a high resolution DEM will be very helpful in the near future to improve fine-scale distribution patterns. Another improvement would be the use of a time series' analysis of NDVI (Normalized Difference Vegetation Index) images that would allow a better evaluation of the snow cover and the different phenologies of vegetation.

The approach here allows optimizing time and field efforts to map vegetation in complex mountain areas. In particular, it will serve as key input within the framework of CarHab project, by providing pre-defined vegetation's series outlines. It is then possible to produce probabilistic maps of vegetation by coupling modelled ecological compartments with physiognomies extracted from remote sensing classification.

In all, graph theory has proven to be suitable to analyse vegetation-plot data under a community-based approach and to propose species assemblages as objects to be modelled across complex landscapes. When vegetation data are available, using SDM with well-defined indicator species in addition to simple and generic explanatory variables allows the production of relevant ecological compartments in conformity with fields' expert knowledge.

VI. Acknowledgments

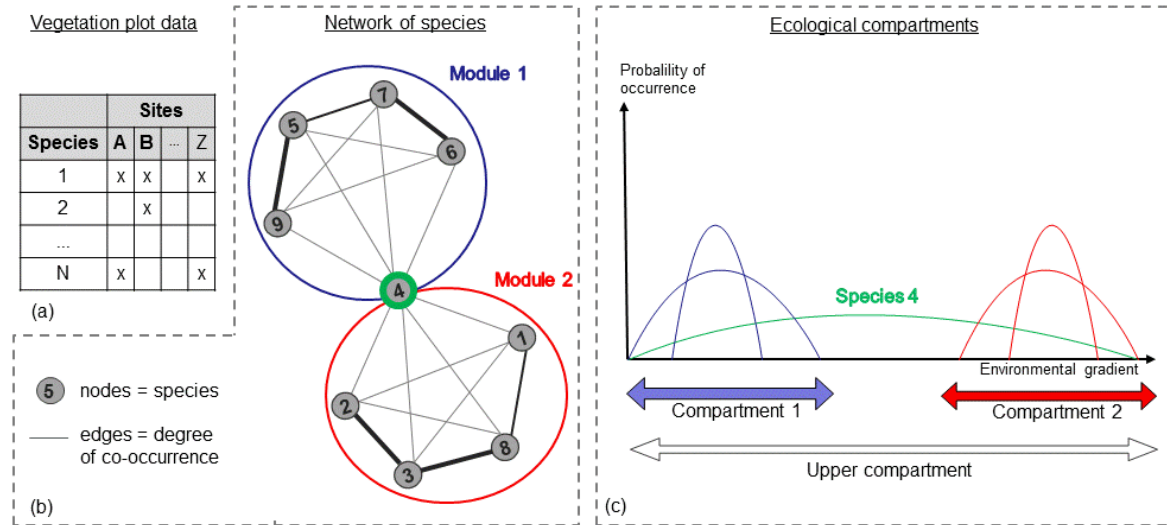
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Graphical abstract

Highlights (max 85 characters per bullet point, including spaces)

- species' geographic distributions supports conservation planning and forecasting
- mapping natural and semi-natural habitats of complex mountain vegetation mosaics
- Spatial approach provides different alternatives for policy makers to help conservation targets
- we propose species assemblages as objects to be modelled across complex landscapes
- graph theory suitable to analyse vegetation-plot data under a community-based approach